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DIMENSIONAL CHANGES IN WIRES DURING COILING OPERATIONS

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When evaluating the properties of coils, either the magnetic field of an electromagnetic coil or the spring-constant of a coiled spring, it is common to assume that the wire's cross section remains the same as in its linear form. In reality, however, changes in this cross section become more pronounced as the ratio of the wire's thickness, H, (in the radial direction of the coil) to that of the coil's inner diameter, ID, approaches 0.05 and above. While these changes are functions of the above-mentioned ratio, they

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20. ABSTRACT (CONT'D)

vary between the coil's ID and its outer diameter, OD. In designing coils for high current density, the ability to compute these changes becomes pertinent, mainly because it affects the minimum available clearance between the coil's loops.

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NOMENCLATURE

B ≡ wire's original width (parallel to the coil's axis) in a rectangular wire

B_i ≡ wire's width at the coil's ID (after winding)

B_o ≡ wire's width at the coil's OD (after winding)

d ≡ cross-sectional diameter of a round wire

D_i ≡ coil's inner diameter

D_o ≡ coil's outer diameter

D_m ≡ coil's neutral axis

h ≡ local thickness of a round wire

h' ≡ distance from neutral axis after winding of a circular wire

H ≡ wire's original thickness (in the radial direction) in a rectangular wire

H_i ≡ wire's "half-thickness" between the coil's neutral axis and its ID after winding

H_o ≡ wire's "half-thickness" between the coil's neutral axis and its OD after winding

H_t ≡ total thickness, $H_i + H_o$, of a (rectangular) wire after winding

q ≡ strain ratio, $\epsilon_{rr}/\epsilon_{xx}$

r ≡ radial direction - a coordinate

r ≡ radial distance from the coil's centerline

t ≡ the horizontal width of a 'distorted' circular cross section at an angle $\pm\phi$ to the horizontal diameter after winding

t_o ≡ a horizontal width of a circular cross section at an angle $\pm\phi$ to the horizontal diameter

t' ≡ width after winding at a distance h' from the neutral axis of the circular wire

x ≡ axial direction - a coordinate

ϵ ≡ strain

ϵ_{rr} ≡ radial strain (normal) on a radial plane in the radial direction

ϵ_{xx} ≡ axial strain (normal) on the axial plane in the axial direction

$\epsilon_{\theta\theta}$ ≡ hoop strain (normal) on a hoop plane in the hoop direction

δ ≡ desired clearance between coil's loops

ϕ ≡ rotational coordinate normal to the wire's axis (for round wires)

ρ ≡ distance from the (round) wire's center to its surface

θ ≡ hoop or tangential coordinate

ψ ≡ the distortion of ϕ due to the deformation of the wire

INTRODUCTION

In designing coils, either to be used as springs or to generate a magnetic field through the passage of an electric current, it is common to calculate the spring-constant in the former or the current density in the latter, based on the cross section of the wire from which the coil is being made. However, during the winding operation the wire is being plastically deformed and its cross-sectional dimensions change. The calculation of such a change, specifically for wires of rectangular cross section, is derived here. A computer program computing such changes and numerical results are presented in this report.

DERIVATIONS

Volume constancy dictates that

$$(1+\epsilon_{xx})\cdot(1+\epsilon_{rr})\cdot(1+\epsilon_{\theta\theta}) = 1$$

The strain in the tangential direction, $\epsilon_{\theta\theta}$, determined by the geometry of the process is

$$\epsilon_{\theta\theta} = \frac{2r - D_m}{D_m} = -1 + \frac{2r}{D_m}$$

or

$$1 + \epsilon_{\theta\theta} = \frac{2r}{D_m}$$

where the neutral diameter, D_m, is

$$D_m = \frac{D_o + D_i}{2} = D_i + H$$

Intuitively, one may assume that the strains in the two mutually orthogonal directions (which are also normal to the θ coordinate), ϵ_{rr} and ϵ_{xx}, are equal. Nevertheless, this investigator derived the equations for the strain field and

the strain energy, thereof, for the general case of any arbitrary strain ratio, $q = \epsilon_{rr}/\epsilon_{xx}$. However, invoking the principle of "minimum energy" yielded an optimal strain ratio of $q = \epsilon_{rr}/\epsilon_{xx} = 1$. Therefore, the following derivations and the computations thereof, will be confined to the assumption that $\epsilon_{rr} = \epsilon_{xx}$. Thus

$$(1+\epsilon_{xx})^2 = \frac{1}{1 + \epsilon_{\theta\theta}}$$

or

$$\epsilon_{xx} = \epsilon_{rr} = -1 + \sqrt{\frac{D_m}{2r}}$$

If $B \equiv$ the wire's width in the coil's axial direction before winding, then its width, B_i, at the coil's inner diameter, ID, will become

$$B_i = (1 + \epsilon_{xx@r=D_i/2}) \cdot B = \sqrt{\frac{D_m}{2r}} \cdot B = \sqrt{1 + \frac{H}{D_i}} \cdot B$$

whereas the wire's width, B_o, in the coil's axial direction at the coil's outer diameter, OD, will be

$$B_o = (1 + \epsilon_{xx@r=D_o/2}) \cdot B = \sqrt{\frac{D_m}{2r}} \cdot B = \sqrt{1 - \frac{H}{D_o}} \cdot B = \sqrt{1 - \frac{H}{D_i + 2H}} \cdot B$$

Thus, any required clearance, δ, at the coil's ID will lead to a clearance of

$$\delta = \left(\sqrt{1 + \frac{H}{D_i}} - \sqrt{1 - \frac{H}{D_i + 2H}}\right) \cdot B$$

at the coil's OD. As H/D_i becomes a significant fraction of 1, the added gap at the coil's OD also becomes significant.

The change in the wire's thickness, H, between the coil's ID and OD is an integrated one. Neglecting changes in the wire's neutral axis with progressing

bend, the respective distance between that axis and the coil's ID, H_i, and that of the coil's OD, H_o, will become

$$H_i = \int_{D_i/2}^{D_m/2} (1+\epsilon_{rr}) \cdot dr = \int_{D_i/2}^{D_m/2} \sqrt{\frac{D_m}{2r}} \cdot dr = \sqrt{\frac{D_m}{2}} \cdot \int_{D_i/2}^{D_m/2} \frac{dr}{\sqrt{r}} =$$

$$2 \cdot \sqrt{\frac{D_m}{2}} \left[\sqrt{\frac{D_m}{2}} - \sqrt{\frac{D_i}{2}} \right] = (D_i + H) - \sqrt{D_i(D_i+H)}$$

and

$$H_o = \int_{D_m/2}^{D_o/2} (1+\epsilon_{rr}) \cdot dr = \sqrt{\frac{D_m}{2}} \cdot \int_{D_m/2}^{D_o/2} \frac{dr}{\sqrt{r}} = 2 \cdot \sqrt{\frac{D_m}{2}} \left[\sqrt{\frac{D_o}{2}} - \sqrt{\frac{D_m}{2}} \right]$$

$$= \sqrt{(D_i+2H)(D_i+H)} - (D_i+H)$$

respectively. Thus, as the wire's thickness to the coil's inner diameter ratio, H/D_i, increases, the wound thicknesses, H_i and H_o, respectively, deviate significantly from the wire's half-thickness, $H/2$. However, as seen in Table I and in Figure 1, the total thickness of the wound wire,

$$H_t = H_i + H_o = \sqrt{(D_i+2H) \cdot (D_i+H)} - \sqrt{D_i \cdot (D_i+H)}$$

deviates insignificantly from its original thickness, H. Thus, unless the neutral axis of the wire is being marked prior to winding, dimensional changes in the radial direction are difficult to detect.

WIRES WITH A CIRCULAR CROSS SECTION

In laying a circular wire of a diameter d against the coiling mandrel of diameter D_i, the wire's width, t_o, will be

$$t_o = \frac{d}{2} \cdot \cos \phi$$

(see Figure 2). Due to strain in the axial direction, ϵ_{xx}, and as a first approximation,

$$t = t_o \cdot (1+\epsilon_{xx}) = \sqrt{\frac{D_m}{2r}} \cdot \frac{d}{2} \cdot \cos\phi = \sqrt{\frac{D_i + d}{D_i + (1+\sin\phi)\cdot d}} \cdot \frac{d}{2} \cdot \cos\phi$$

At the same time, the distance,

$$h = \frac{d}{2} \cdot \sin\phi$$

(of a line parallel to the coil's axis) from the wire's original center will become

$$h' = \int_{D_m/2}^{D_m/2+h} (1+\epsilon_{rr}) \cdot dr = \sqrt{(D_i+d)\cdot[(D_i+d) + h]} - (D_i+d) =$$

$$\sqrt{(D_i+d)\cdot[D_i+(1 + \frac{\sin\phi}{2})d]} - (D_i+d)$$

Thus, any original width of $t = \frac{d}{2} \cdot \cos\phi$ at a distance of $h = \frac{d}{2} \cdot \sin\phi$ from the wire's center will become

$$t' = \sqrt{\frac{D_i + d}{D_i + (1+\sin\phi)\cdot d}} \cdot \frac{d}{2} \cos\phi$$

at a new distance of

$$h' = \sqrt{(D_i+d) \cdot [D_i + (1 + \frac{\sin\phi}{2}) \cdot d]} - (D_i+d)$$

from the wire's center. Similarly, each angle ϕ will be transformed to

$$\psi = \sin^{-1} \frac{2h'}{\rho} = \sin^{-1} \frac{\sqrt{(D_i+d) \cdot [D_i + (1 + \frac{\sin\phi}{2}) \cdot d]} - (D_i+d)}{\rho}$$

where

$$\rho = \pm \sqrt{(h')^2 + (t')^2}$$

Thus, at

$$\phi = \pm \frac{\pi}{2} \quad , \quad t' = 0$$

$$\psi = \sin^{-1}(\pm 1) = \pm \frac{\pi}{2} \qquad \text{Q.E.D.}$$

and at

$$\phi = 0 \quad , \quad h' = 0$$

and thus

$$\psi = \sin^{-1}(0) = 0 \qquad \text{Q.E.D.}$$

RESULTS AND CONCLUSIONS

The computer program for the calculation of the previously mentioned dimensional changes that take place during winding of the wires of rectangular cross sections is given in Figure 3. The results of the wire's thickness to the coil's inner diameter ratios in the range of $H/D_i = 0.04494$ to $H/D_i = 0.21573$ are given in Table I together with the relative changes in the wire's cross-sectional area (measured normal to its local axis). These results are also summarized in Figures 1 and 4.

The above is based on the assumption that all three principle components of strain are functions of distance from the coil's centerline only. Unfortunately, experimental results suggest otherwise. If the above assumptions would have prevailed, wires having rectangular (or square) cross sections would have been deformed into a symmetrical trapezoid. In reality, however, the shape of the cross section changes into one that resembles a segment of a ring as shown in Figure 5, with the wider and convex side facing the coil's ID, while the narrower and concave side is on the coil's OD. The mechanism by which this deformation takes place is not clear. However, precise measurements of actual deformations might lead to a better approximation of the deformation field and

thus of future predictions of the dimensional changes associated with the winding of rectangular wires.

If, indeed, current density is crucial, and unevenness of the gap between loops is undesirable, such a knowledge can allow the designer to dictate the prewinding cross-sectional shape of the wire that will yield a near-rectangular wound wire.

TABLE I. CHANGES IN WIRE'S CROSS SECTION UPON WINDING OVER A 2.225-INCH ROUND MANDREL

H	H/D_i	B_i/B	B_o/B	$(B_i-B_o)/B$	$2H_i/H$	$2H_o/H$	H_t/H	Normalized Area
0.10000	0.04494	0.10222E+01	0.97916E+00	0.43061E-01	0.10110E+01	0.98948E+00	0.10002E+01	0.10009E+01
0.12000	0.05393	0.10266E+01	0.97536E+00	0.51257E-01	0.10131E+01	0.98751E+00	0.10003E+01	0.10013E+01
0.14000	0.06292	0.10310E+01	0.97165E+00	0.59326E-01	0.10153E+01	0.98562E+00	0.10004E+01	0.10018E+01
0.16000	0.17191	0.10353E+01	0.96806E+00	0.67275E-01	0.10174E+01	0.98376E+00	0.10006E+01	0.10023E+01
0.18000	0.08090	0.10397E+01	0.96456E+00	0.75107E-01	0.10194E+01	0.98197E+00	0.10007E+01	0.10028E+01
0.20000	0.08989	0.10440E+01	0.96115E+00	0.82827E-01	0.10215E+01	0.98019E+00	0.10009E+01	0.10034E+01
0.22000	0.09888	0.10483E+01	0.95784E+00	0.90438E-01	0.10236E+01	0.97847E+00	0.10010E+01	0.10041E+01
0.24000	0.10787	0.10526E+01	0.95461E+00	0.97944E-01	0.10256E+01	0.97678E+00	0.10012E+01	0.10048E+01
0.26000	0.11685	0.10568E+01	0.95146E+00	0.10535E+00	0.10276E+01	0.97513E+00	0.10014E+01	0.10055E+01
0.28000	0.12584	0.10611E+01	0.94840E+00	0.11266E+00	0.10296E+01	0.97352E+00	0.10016E+01	0.10063E+01
0.30000	0.13483	0.10653E+01	0.94541E+00	0.11987E+00	0.10316E+01	0.97194E+00	0.10018E+01	0.10071E+01
0.32000	0.14382	0.10695E+01	0.94250E+00	0.12699E+00	0.10336E+01	0.97040E+00	0.10020E+01	0.10080E+01
0.34000	0.15281	0.10737E+01	0.93966E+00	0.13403E+00	0.10355E+01	0.96889E+00	0.10022E+01	0.10089E+01
0.36000	0.16180	0.10779E+01	0.93689E+00	0.14098E+00	0.10375E+01	0.96741E+00	0.10024E+01	0.10098E+01
0.38000	0.17079	0.10820E+01	0.93418E+00	0.14785E+00	0.10394E+01	0.96597E+00	0.10027E+01	0.10108E+01
0.40000	0.17978	0.10862E+01	0.93154E+00	0.15463E+00	0.10413E+01	0.96456E+00	0.10029E+01	0.10118E+01
0.42000	0.18876	0.10903E+01	0.92896E+00	0.16134E+00	0.10432E+01	0.96317E+00	0.10032E+01	0.10128E+01
0.44000	0.19775	0.10944E+01	0.92644E+00	0.16798E+00	0.10451E+01	0.96181E+00	0.10034E+01	0.10139E+01
0.46000	0.20674	0.10985E+01	0.92398E+00	0.17454E+00	0.10469E+01	0.96049E+00	0.10037E+01	0.10150E+01
0.48000	0.21573	0.11026E+01	0.92157E+00	0.18103E+00	0.10488E+01	0.95918E+00	0.10040E+01	0.10161E+01

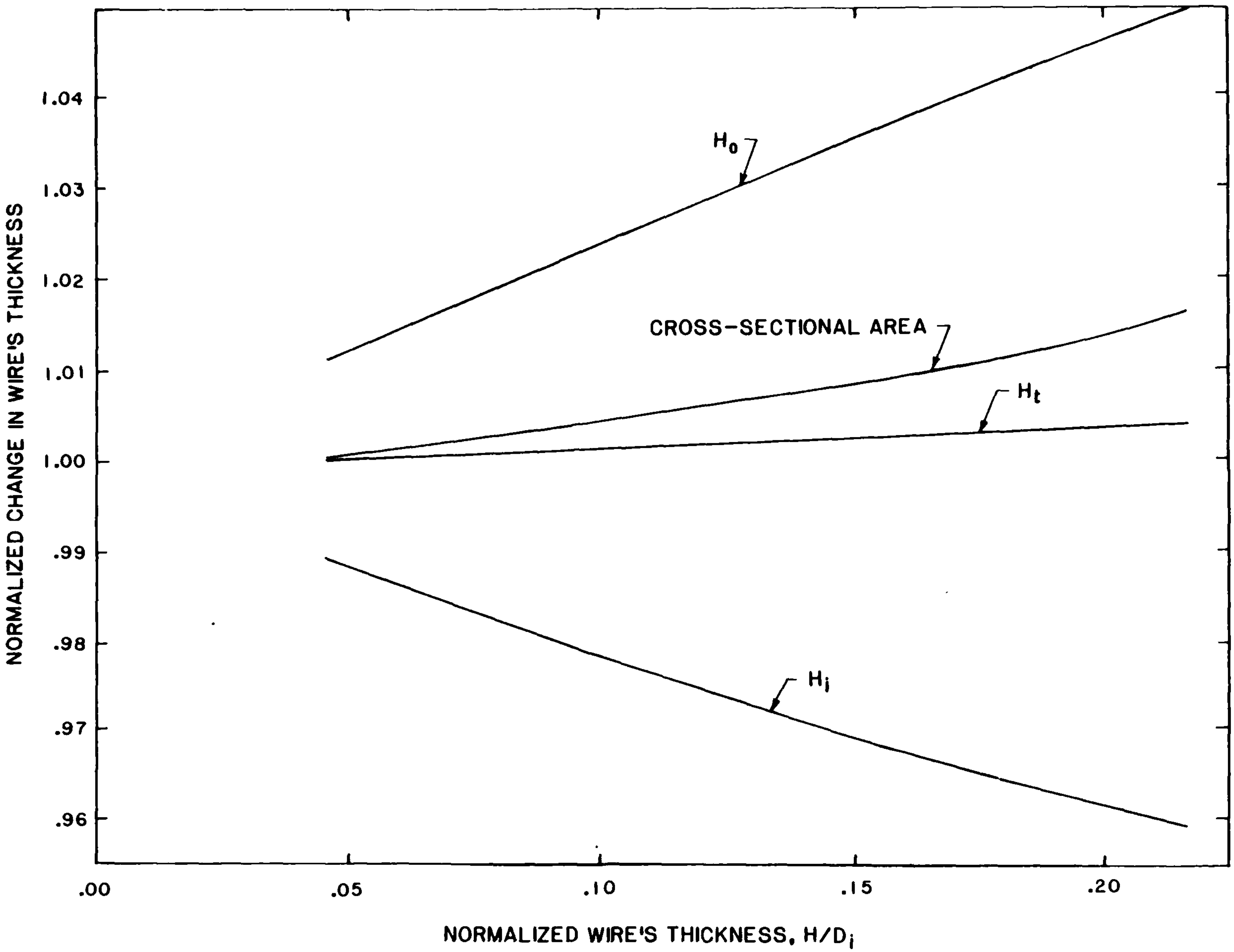

Figure 1. Changes in (rectangular) wire's thickness as a function of original thickness to coil's diameter ratio.

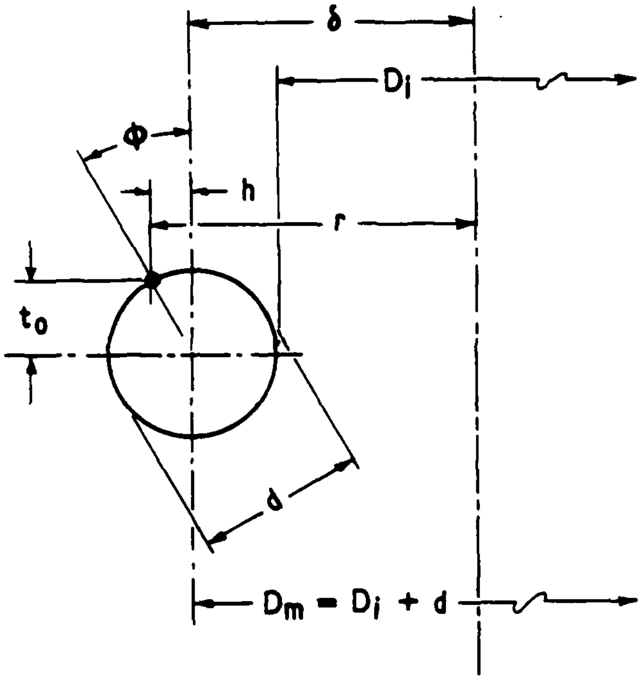

Figure 2. Coordinates and dimensional notations for a circular wire in a coil.

```
200   READ (1, 105, END=99) H1,DI,DEL,K
105   FORMAT (3F10.5,I5)
      WRITE (6,610) DI,H1
      H=H1
      DO 100 I=1,K
      DO=DI+2.*H
      HR=H/DI
      BI=SQRT(1.+HR)
      BO=SQRT(1.-H/DO)
      BIO=BI-BO
      ROOT1=SQRT(DO*(DO+DI)/2.)
      ROOT2=SQRT(DI*(DO+DI)/2.)
      HT=(ROOT1-ROOT2)/H
      HO=2.*(ROOT1-(DO+DI)/2.)/H
      HI=2.*((DO+DI)/2.-ROOT2)/H
      AREA=(BO+BI)*HT/2.
      WRITE (6,620) H,HR,BI,BO,BIO,HI,HO,HT,AREA
100   H=H+DEL
610   FORMAT('  THE FOLLOWING  ARE THE CALCULATED CHANGES IN WIRE S DIME
     +NSIONS, UPON COILING.',/,'  AROUND A CORE DIAMETER OF      DI=',E15
     +.5,/,' STARTING WITH WIRES  HEIGHT OF H1=',E15.5,/,4X,'H',9X,'HR',
     +10X,'BI',12X,'BO',11X,'BIO',12X,'HI',12X,'HO',12X,'HT',11X,'AREA')
620   FORMAT(2F9.5,7E14.5)
 99   CALL EXIT
      END
```

Figure 3. A computer program (in FORTRAN IV).

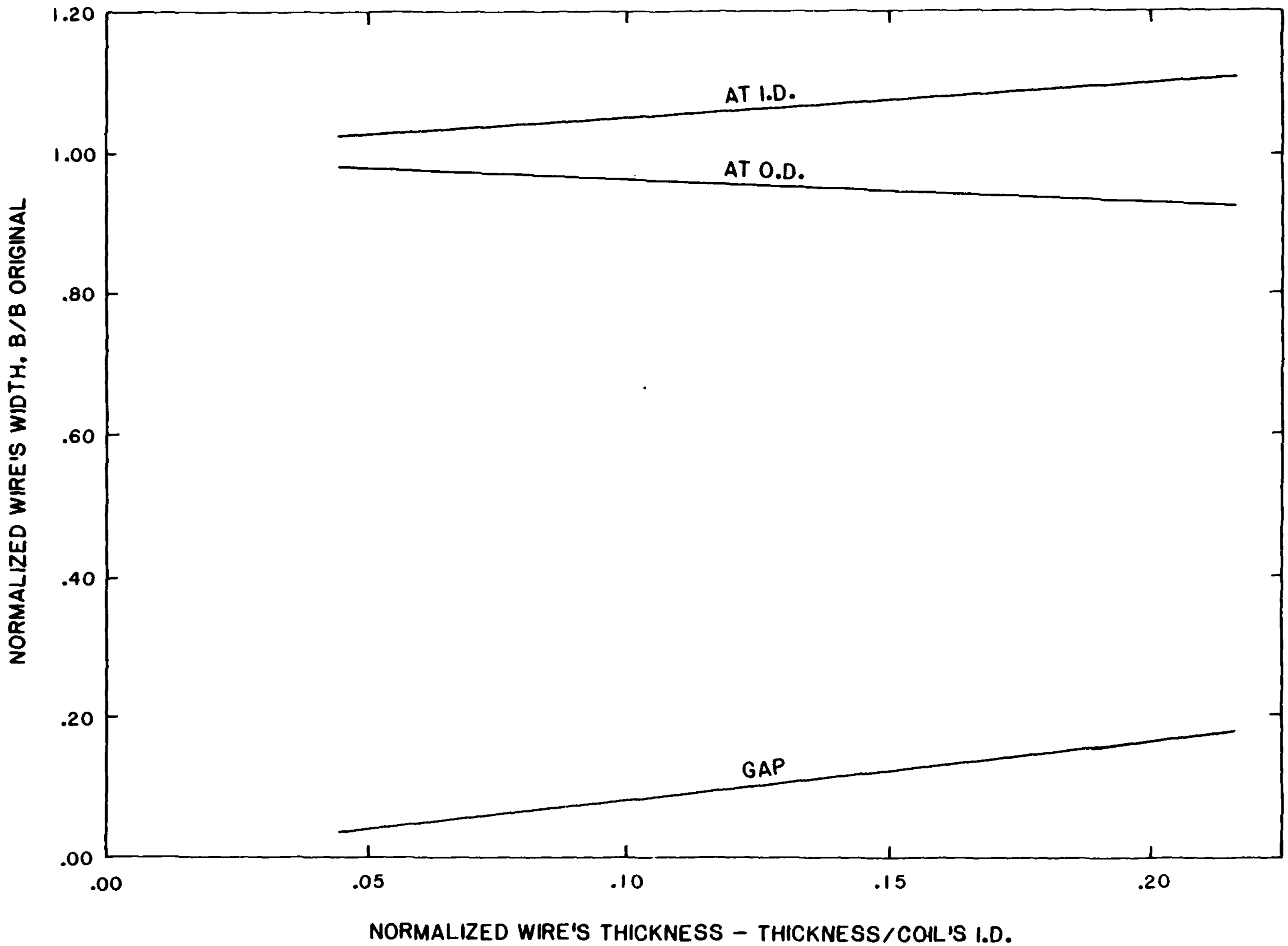

Figure 4. Changes in (rectangular) wire's width as a function of original thickness to coil's diameter ratio.

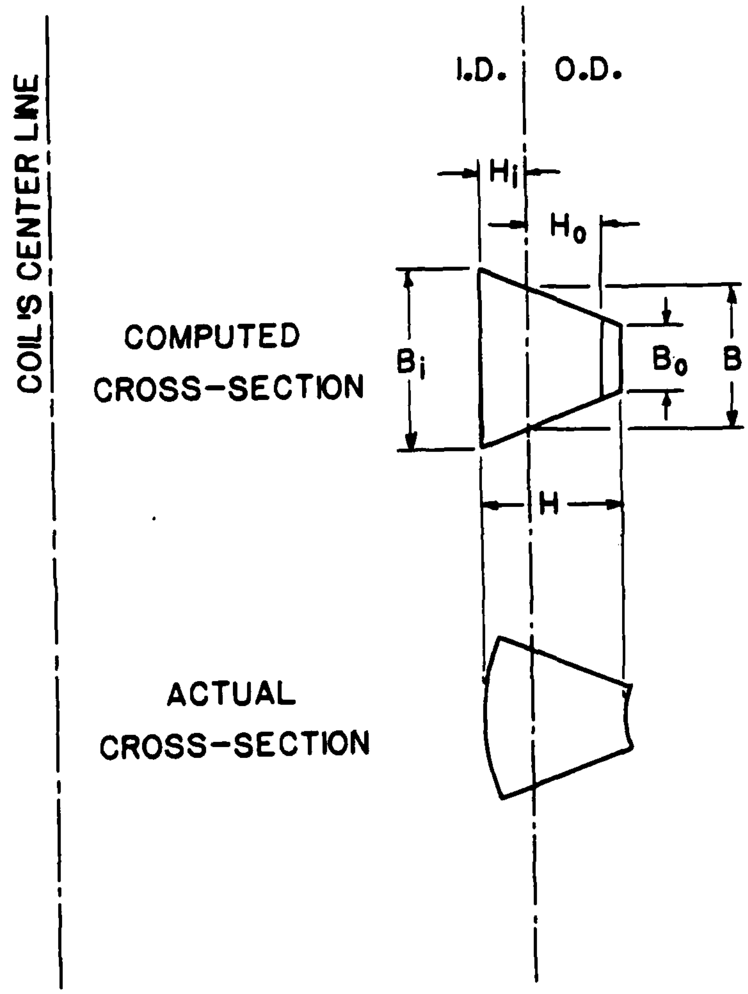

Figure 5. Schematic comparison of computed change with the actual change in wire's cross section.

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